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Deep Mineral Resources

Current Research Projects
Supported by the Integrated Basic
Research Program

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Foreword

In 1978 the National Science Foundation (NSF) established a program of Integrated Basic Research (IBR) in order to bridge more effectively its applied science responsibilities and its central mission of support for discipline oriented basic research. Implementation of this objective is accomplished through IBR split-funding participation with NSF basic research divisions on projects that contribute to certain topics. Thus, research proposals that are found to be meritorious in a basic scientific discipline may benefit from partial IBR funding if they also have an application potential in a particular topic.

As an applied science program, IBR provides partial funding on existing or emerging major topics, solutions to which require greater fundamental understanding. Major problems of scientific interest were identified through a broad consultation with scientists across the country. The IBR advisory subcommittee reviewed candidate topics and recommended support for eight topics. Four of these received major funding emphasis in FY 1979, and four additional topics were given minor exploratory support. One of the major topics was Deep Mineral Resources, which is the subject of this report.

In the IBR topic of Deep Mineral Resources, NSF has established in FY 1979 its first basic research program exclusively related to ore deposits. Drawing on $5.2 million of new basic research effort in the earth and ocean sciences, engineering, and computer science, the IBR topic focuses academic science attention on new knowledge in the origins of ore deposits, mineral exploration, and extraction of mineral values by *in situ* leaching. By adding $1.2 million to $4 million of disciplinary science program funds in joint funding of 49 basic research projects, IBR has identified and augmented a core program of science in support of long range U.S. needs in non-fuel mineral resources.

In the pages that follow, I trust that you will find an exciting story of basic research actively being conducted at this moment and promising large dividends for the Nation's mineral resource future. These projects are sponsored by NSF, and you are invited to contact us or the Principal Investigator for further information on projects of interest to you.

Jack T. Sanderson

Introduction

Needs for energy and mineral resources will continue to increase and in various ways will strain the finite Earth's ability to supply raw materials and fuels economically. Because of its highly industrialized economy and interdependent urbanized society, the U.S. is particularly vulnerable to gradual exhaustion of indigenous resources and interruption of foreign supplies.

Stringency of energy supply was graphically demonstrated in the oil embargo of 1973, and rapidly increasing prices of many fuels are new and viral sources of inflation in the U.S. While materials shortages do not appear imminent as in the case of energy, the case for the U.S. mineral future is equally a matter of concern. In 1979, the U.S. imported more than half its requirements in 19 mineral commodities, and the list has been as high as 22 in recent years. There may be times in the future when we will need to reverse this trend and rely more heavily on domestic sources of supply.

However, outside of Alaska, the U.S. is one of the most thoroughly prospected regions of the world. This means that the large shallow deposits of high grade ore have been found and mined. Thus expansion of the domestic resource base depends on low grade and small deposits and on deep deposits. Although technology is available for mining and processing low grade ore, energy requirements are costly. Small deposits lack the economies of scale necessary for profitable mining. Therefore, deep mineral deposits hold large importance for future mineral supplies if the science and technology become available for exploiting them.

Extensive mineral wealth is potentially available at depths of 1 mile or more below ground if deposits can be found and mined successfully. These ore deposits lie beneath masking veneers of non-ore materials on the continents and on the continental margins. If these mineral resources can be found and recovered, utilizing a new, expanded scientific base, the deep reserves will contribute decisively to our long range mineral security. (Attention is given to non-fuel minerals only.)

Conventional mining at large depths will become increasingly prohibitive for reasons of safety and energy costs and large investment requirements. Mining by *in situ* methods offers an alternative means of mineral extraction where surface methods (strip mining) and conventional mining are not feasible. In addition, solution mining promises a significant improvement in miner safety and reduced disturbance of the surface environment. Thus, the two areas of research emphasis in Deep Mineral Resources are Mineral Exploration Science and Solution Mining.

To maintain a broad and alert overview on the importance of science in mineral resources, IBR has supported the National Academy of Sciences (NAS) in its "Studies in Geophysics" (NSF Grant EAR 79-02458). Through its Geophysics Research Board (GRB) the NAS performs studies dealing with timely scientific and societal aspects of geophysics and the corresponding demands for new geophysical knowledge. These studies, combined with suitable summary volumes, are published in a series called Studies in Geophysics. Two studies recently concluded are pertinent to the topic of Deep Mineral Resources. They are the *Mineral Resources* and *Continental Tectonics* studies. These studies provide evaluations of research needs and opportunities that will help in future guidance of NSF research related to mineral resources. Important background is available in these reports with perspectives on the state of scientific knowledge with respect to needs.

I. Solution Mining

Today, conventional mining is by means of open pit methods and at greater depth by excavation of large volumes of rock through extensive underground openings. Thus conventional deep mining is energy intensive because a small amount of metal (1% or less) is recovered from a large volume of rock and capital intensive because of the large underground works prerequisite to mine production. In the future era which appears now to be opening, in which energy and capital stringency are common economic conditions, conventional mining at large depths will become increasingly prohibitive. Not only will energy costs and large investment requirements mitigate against new deep mines, but considerations of safety to miners and damage to the surface environment will also handicap the conventional approach.

Mining by *in situ* methods (or solution mining) is an alternative means of mineral extraction where surface methods (open pit mining) and conventional deep mining are not feasible. In addition, solution mining promises a significant improvement in miner safety and reduced disturbance of the surface environment.

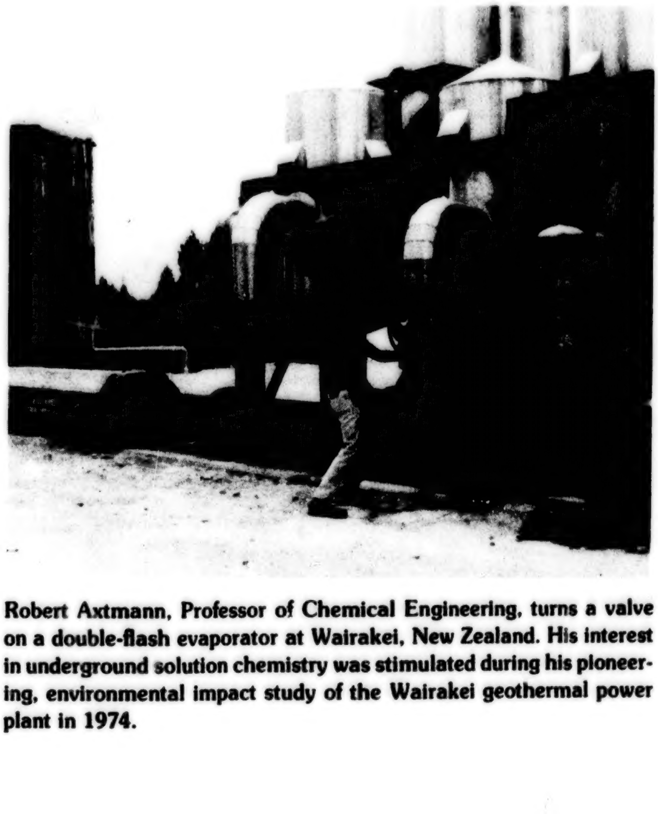
In situ methods generally involve the injection of leaching solutions into a deep ore body via boreholes. These solutions circulate through tiny apertures in the rocks, reacting chemically with the minerals they encounter. Mineral values are selectively taken into solution and flow to the surface via production wells, where metals are recovered by hydrometallurgical processes. The leaching solution is recharged and reinjected into the ore body.

A. Solution Chemistry

Complex geochemical environments are anticipated in an ore deposit and surrounding host rocks. Large gaps in the scientific knowledge of leaching and other chemical reactions must be closed in order for future solution mining technologies to be developed. Some of the gaps include needed new understanding in the kinetics of multicomponent leaching solutions, control of dissolution and reprecipitation reactions, surface chemistry of silicate and ore minerals, and reservoir engineering of chemically active solutions. Five new research projects were started in 1979 that contribute new knowledge to fill these gaps.

Fundamental Studies of Silica Polymerization and Deposition *Robert C. Axtmann and Dudley A. Saville*, Princeton University, Princeton, New Jersey.
NSF Research Program: Particulate & Multiphase Processes
Grant No: ENG 79-15160

Silica (SiO_2) is the most common rock forming mineral in the earth's crust. Chemical reactions of silica in aqueous



Robert Axtmann, Professor of Chemical Engineering, turns a valve on a double-flash evaporator at Wairakei, New Zealand. His interest in underground solution chemistry was stimulated during his pioneering, environmental impact study of the Wairakei geothermal power plant in 1974.

(water) solutions are very complex, and much still needs to be learned on how silica polymers (large molecules) grow and precipitate as solids. These reactions are involved wherever solutions circulate through earth materials.

Research on silica chemistry has wide application potential. It contributes to better understanding of subjects ranging: from the growth of chert on the ocean floor to the control of boiler scale; from petrogenesis of siliceous rocks to solution mining of ore bodies; and from production of synthetic opal and commercial silica to reinjection of geothermal fluids.

At Princeton University, chemical engineers are studying the chemistry and physics of silica solutions. Their findings may enhance understanding of underground transport of aqueous silica, which is essential in ore formation and chemical alteration of rock. If quantitative, predictive theories for silica precipitation can be obtained, difficulties caused by unwanted silica-water reactions encountered in the mineral leaching process may be reduced or avoided completely.

The Water Sensitivity of Sandstones; *H. Scott Fogler,* University of Michigan, Ann Arbor, Michigan.
NSF Research Program: Particulate & Multiphase Processes
Grant No: ENG 79-06647

A major problem facing the oil and gas industries is reduced permeability of sandstone reservoirs. Lower permeability caused by the swelling or compaction of clay particles and the subsequent blocking of pores in the sandstone, has serious consequences in terms of decline in hydrocarbon production.

Water sensitivity is the colloidal phenomenon leading to decreased permeability. If it could be understood, the new knowledge would benefit not only gas and oil production in control of the problem, but it could also ease permeability problems encountered in solution mining operations. The leaching solutions must have access to the ore minerals.

W.E. Kline, Ph.D. candidate in chemical engineering at the University of Michigan, prepares to withdraw a sample from the slurry reactor in mineral dissolution experiments while the Principal Investigator, Scott Fogler, looks on.

The water sensitivity phenomenon involves fundamental processes such as flocculation, peptization, filtration, and adsorption. The Michigan project involves experiments to evaluate the important parameters governing water sensitivity such as flow rate and rate of saline flooding. In addition, the researchers are developing a theoretical model of the loss of permeability in order to resolve discrepancies in the technical literature on water sensitivity.

Synthesis, Stabilities and Element Distribution of Minerals under Hydrothermal Conditions
J. G. Liou, Stanford University, Stanford, California.
NSF Research Program: Geochemistry
Grant No: EAR 79-09138

Two-thirds of the earth's crust is composed of oceanic basalt undergoing some degree of metamorphism, i.e., mineral alteration due to high temperature and pressure. However, the metamorphic history of basaltic rocks remain imprecise. Research in this area is interesting in that it clarifies geochemical processes occurring at divergent and convergent plate boundaries, where basalts and other rocks are subjected to intense heat and pressure.

At Stanford University, faculty members and graduate students are investigating the petrology of low grade

Peter Gordon, Senior Laboratory Mechanic, loads a mineral sample to a specially designed gold bag that is the heart of the Dickson-type hydrothermal test apparatus. After the assembly in his hands is inserted in a high temperature-pressure vessel, hot solutions are circulated through the mineral sample. The gold does not react chemically with the solutions and thereby interfere with experimental results.

metamorphism and hydrothermal alteration of basaltic-andesitic rocks. Their research should improve knowledge of leaching chemistry which is important in solution mining operations. Although commercial solution mining operations are not likely to produce the high temperature and pressure of which Nature is capable, the action of mineral laden solutions in altering rock is a subject of overlapping interest.

Stanford's experimental techniques involve the use of Dickson-type hydrothermal apparatus and conventional static methods. The investigators wish to determine the stability fields of metamorphosed basalts in terms of pressure, temperature and geochemical composition.

Experimental Determination of Solubilities and Solution Equilibria of Rock-Forming Minerals *John V. Walther and Philip M. Orville* Yale University, New Haven, Connecticut.
NSF Research Program: Geochemistry
Grant No: EAR 79-04892

Despite the need for information on the solubility of geologically important oxides, hydroxides, and carbonates, research in this area is slow because it is difficult to make geochemical measurements in aqueous solutions at very high temperatures (300 to 750 degrees Celsius) and pressures (up to 3 kilobars).

This research project is expected to reveal important information on how chemically active aqueous solutions work in rockforming and dissolution processes. Improved knowledge of these processes would enhance the scientific understanding of solution mining chemistry. The variability of mineral solubilities over wide temperature and pressure ranges will be useful data in planning solution mining operations, particularly in the low-to-moderate temperature range. However, as solution mining is attempted at greater depths, the upper range of temperature and pressure may become more important.

Geologists at Yale University are trying to collect solubility data not yet obtained experimentally. The data are essential to understanding any petrological process involving an aqueous fluid. Although the data will be difficult to interpret, researchers remain optimistic that this project is an important first step in a systematic attack on the problem.

Interfacial Chemistry of Selected Fine Particles Processing Systems *P. Somasundaran,* Columbia University, New York, New York.
NSF Research Program: Particulate & Multiphase Processes
Grant No: ENG 78-25213

A major problem in the mining industry today is the lack of technological know-how to recover values from lower quality domestic ores that are left over from depleted shallow mines. The situation is characterized by larger and larger amounts of mineral fines and ultrafines generated during mining and milling and discarded for lack of the processing technology compatible with current energy, cost and environmental limitations.

K. P. Ananthapadmanabhan, graduate research assistant, operates streaming potential apparatus in study of changes in Zeta potential of minerals due to dissolution, leaching and adsorption.

In approaching this problem, researchers at the Henry Krumb School of Mines of Columbia University are investigating interfacial chemistry and hydrodynamics of fine particles, particularly those dissolution and leaching processes which are also important in solution mining. Solution mining may become an important means of recovering minerals from deep low grade deposits.

By studying the interfacial chemistry of fines and ultrafines in solutions, Columbia engineers hope to understand the role of key chemical factors such as reagent structure, pH, temperature, and ionic strength on the processes of flocculation and aggregation. The problem in deep solution mining, to which this research relates, is the behavior of fine particles in the presence of leaching solutions. It is well known that explosions, used to fracture an ore body, will also produce fines concentrated in the vicinity of the detonation. These fines will tend to impede circulation so that means for their chemical removal must be found in terms of their basic interfacial chemistry.

B. Rock Mechanics

Effective solution mining methods will depend on access of leaching fluids to ore minerals through cracks and pore spaces in the rocks. Large confining pressures at depth tend to make very "tight" or impermeable rock formations. The rock mechanics problem is then to enhance permeability in the ore body by hydraulic or explosive means and maintain it during leaching operations. Such a big problem requires new basic knowledge for innovative new approaches. Five IBR-supported research projects were initiated in 1979.

Fracture Energy of Rock in Chemically Active Environments

Robert B. Gordon, Yale University, New Haven, Connecticut.
NSF Research Program: Geotechnical Engineering
Grant No: EAR 78-24531

Permeability of the ore body is a serious limiting factor on the feasibility of deep solution mining. To increase control over crack growth in rocks, Yale University geologists are exploring the possibility that crack propagation may be facilitated by the presence of chemically reactive fluids. The study would enhance technology in fracture and/or rubblization of deep rock for solution mining purposes.

The objective of the experiment is two-fold. First, researchers wish to determine crack growth characteristics under conditions of temperature, pressure, and fluid phase composition similar to those where slow crack growth is thought to occur in the earth's crust. Second, scientists hope to observe the chemical and physical processes that control stress-corrosion cracking.

The data collected may also be applied directly to problems such as the calculation of the spacing of tension joints in rock or the relief of stresses around underground openings such as a conventional mine.

L.M. Peck (left) and C.C. Barton (center) graduate students, conduct a controlled crack growth experiment on double cantilever beam sample of sandstone. Robert Gordon, Professor of Geophysics and Applied Science, watches the recording of force and crack displacement. A motion picture of the advancing crack is also an important record of the experiment.

Experimental Study of Physical Processes During Tertiary Creep

Hartmut A. Spetzler and Ivan C. Getting, University of Colorado, Boulder, Colorado.
NSF Research Program: Geophysics
Grant No: EAR 79-05281

Geophysicists at the University of Colorado are exploring the origins and consequences of fractures during the final stage of rock failure. By casting light on methods of controlling instability and ultimate failure of rocks, the research may increase the application potential of hydraulic fracturing techniques essential to deep solution mining. Research findings will also facilitate the interpretation of available seismological data.

Failure of brittle rocks results from time-dependent strain known as "creep." Creep is divided into three stages: primary (transient) creep; secondary (steady-state) creep; and tertiary creep. Of the three, tertiary creep has received the least research attention.

In the Colorado study, investigators are examining how confining pressure, pore pressure, and temperature affect tertiary creep of rock, and how cracks grow and interact during creep. The study emphasizes the time and space variations of strains and physical properties during creep, rather than a single static value occuring at the onset of tertiary creep. Measurements of axial and radial strains, surface deformation, ultrasonic wave velocity, and acoustic emissions are also made.

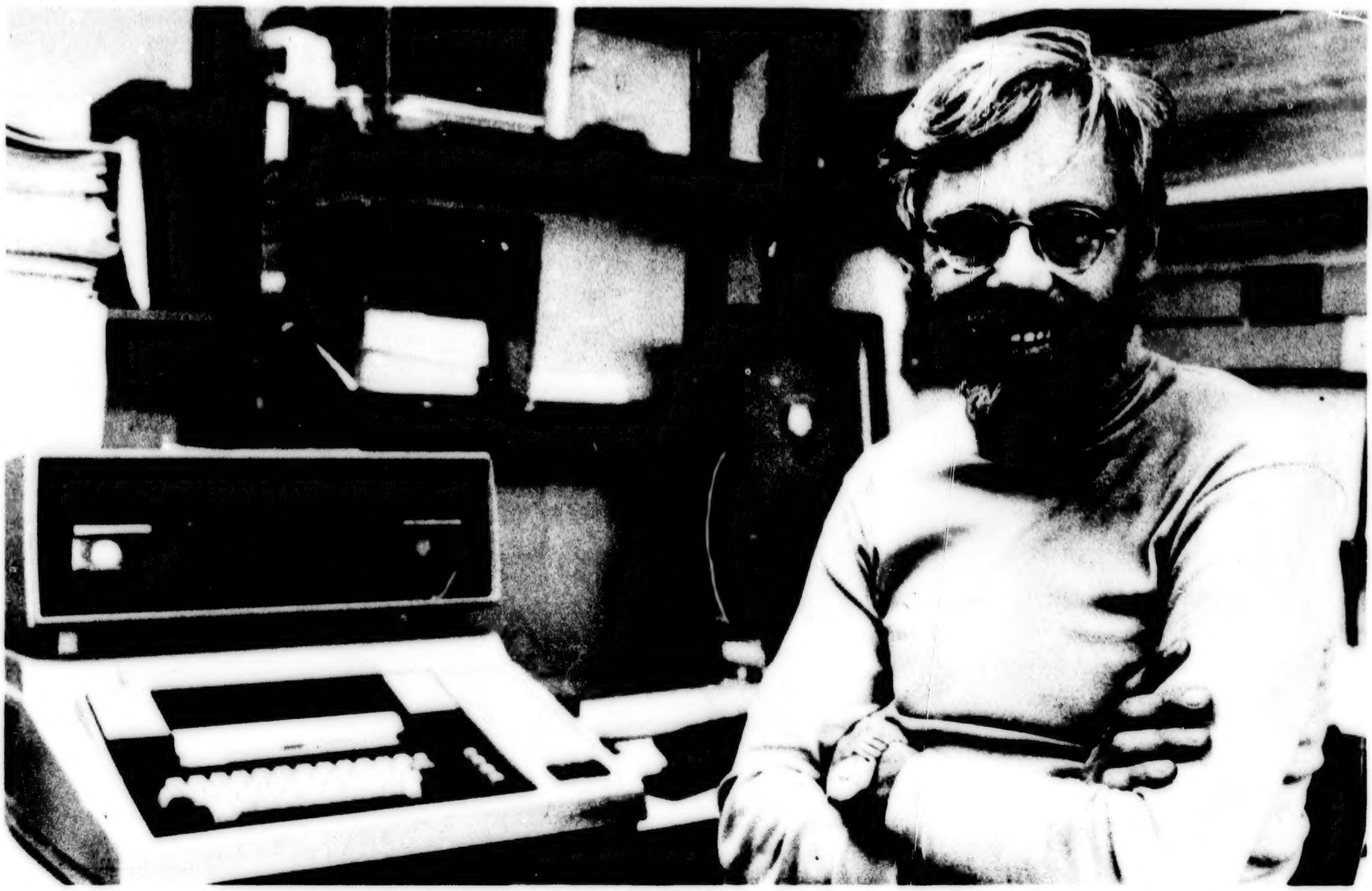
Evaluation of Small Changes in the Crustal Electrical Conductivity of an Active Earthquake Fault Using Natural Geomagnetic Variations

Arthur F. Kuckes, Cornell University, Ithaca, New York.
NSF Research Program: Geophysics
Grant No: EAR 79-05715

Arthur Kuckes is refining a method of predicting earthquakes by measuring stress-induced conductivity changes along a fault line. When a rock is stresed, as it is just before an earthquake, much of the deformation is absorbed by microfractures and pores rather than by the crystal structure of the rock, itself. Since electrical conductivity of buried rock increases markedly in the presence of the conducting fluids, conductivity changes vary with the amount of strain and resultant volume of microcracks. This is especially true when the rock is close to its fracture point when microfractures begin opening.

Changes in the electrical conductivity of stressed rocks is approximately 100–1000 times the change in strain. Thus measurements of conductivity changes is a sensitive indicator of rock deformation at depth. The Cornell research seeks to verify the possibility of detecting 0.2 percent stress-induced conductivity changes.

An additional practical benefit of the project is its potential application to solution mining operations. If pre-earthquake strains can be detected and measured at hypocenter depths in the lower crust, the technique may sense strains induced in ore bodies by hydraulic fracturing. Thus greater control may be exercised in permeability enhancement for deep solution mining.



Arthur Kuckes, Professor in Cornell's School of Applied & Engineering Physics, takes a brief respite from computer calculations of stress-induced conductivity changes.

Research in Geological Physics (Crack Growth and the Thermoelastic Behavior of Rocks)

Ronald L. Shreve, University of California, Los Angeles, California.

NSF Research Program: Geophysics

Grant No: EAR 76-22484

UCLA geophysicists are studying the stress-dependent growth of cracks in rocks and the resulting changes in thermoelastic behavior. This project is a continuation of ongoing NSF-sponsored research on crack growth in rocks containing internal stresses. The study is basic research with potential application to deep solution mining.

An understanding of crack growth, along with information on the composition and structure of an ore body, will assist evaluation of fracturing techniques in increasing the permeability of the ore and the area of crack surface exposed for leaching. Detailed investigation of crack growth also contributes to the understanding and eventual prediction of earthquakes.

The UCLA research consists of four parts: 1) Theoretical study relating crack growth and thermoelastic behavior; 2) Numerical simulation of the behavior of rocks during and after unroofing and unloading; 3) Experimental determination of the relation of growth velocity to intensity factor for cracks in silicate glasses and minerals; and 4) Theoretical evaluation of a postulated mechanism for the growth of joints and sheeting fractures.

William Bruner, Postgraduate Graduate Research Geologist, measures crack growth velocity in quartz specimen mounted on the instrumented stage of the microscope while Ron Shreve, Professor of Geology and Geophysics, looks on. Device in left foreground is servomechanism for controlling the stress-intensity factor for the growing crack.

Effect of Particle Size Distribution and Flow Non-Uniformities on Dispersion in Porous Media *Ruben G. Carbonell*, University of California, Davis, California.

NSF Research Program: Particulate & Mutliphase Processes

Grant No: ENG 79-13269

The flow of leaching solutions through an ore body affects the efficiency of solution mining operations. When rock is fractured explosively, fine particles are produced in a wide variation in size and distribution in the porous rock. They can cause complex fluid flow patterns.

The UC Davis project is an experimental testing of theoretical models of the fluid flow effects of non-uniformities in porous media. In the laboratory size distribution of particles are controlled in a packed bed, and the dispersion of a tracer in a carrier fluid is observed. In addition, particle sizes are varied according to position in the packed bed, thus producing non-uniformities in the porous medium, and the dispersion effects are measured also by tracer methods.

Ongoing research at UC Davis addresses these flow problems, which are related but not limited to shale oil recovery, geothermal reservoirs, and *in-situ* solution mining. Corollary problems to be investigated include tracer analyses of underground coal gasification fields, and groundwater flows in nuclear waste disposal sites.

Dennis Hoagland (left), graduate student, and Ruben Carbonell, Asst. Professor, inspect shipment of plastic spheres to be used in the packed column flow-through experiments.

II. Mineral Exploration Science

Before an ore deposit can be mined, by either leaching or conventional means, it must be *found* and identified as having sufficient economic value to warrant commercial development. This means mineral exploration technology must be capable of detecting and assessing deep ore deposits. This capability, in turn, will rest not only on new instruments to detect anomalous concentrations of minerals, but more importantly on new knowledge of how Nature has produced and disguised ore deposits.

This field of study has been known as economic geology, an earth science discipline that advanced rapidly in the years 1895–1920 in terms of scientific ingenuity and broad understanding of the origins of ore deposits. Prominent among researchers in economic geology was Waldemar Lindgren, whose magnum opus "Mineral Deposits" (1913) has been the standard reference of mining geologists to the present time. Since his time, the principal frontiers of advancement in the earth sciences have been in other areas, e.g., geochronology and isotope geochemistry, lunar and planetary science, and geodynamics and plate tectonics.

Although ore deposits have diminished as direct objects of basic research in academic institutions, the science of ore deposits is presently the fortunate beneficiary of recent momentous expansions in these other disciplines in the earth sciences. For instance, we now understand that the crust of the earth consists of vast rigid plates that are in motion relative to one another. This new framework of global plate tectonics promises continuing new insight on the origin of ore deposits where the earth is in motion and where great heat and pressure at plate margins are mobilizing and redistributing the elements.

This and other exciting areas of scientific advance are contributing to a new synthesis in the geology of ore deposits and the means of finding them at remote depths. In Fiscal Year 1979 IBR supported 38 research grants in mineral exploration, and these are described on the following pages in four areas of principal scientific interest.

A. Geodynamics

Geodynamics is the study of the earth's large scale movements, in particular, the origin, motion and dismemberment of rigid crustal plates and the thermal and geochemical processes associated with the plates. NSF research in geodynamics that has high potential of application in deep mineral exploration includes the following twelve projects related to: plate collisions with Andean type mountain building; oceanic volcanic arcs and arc-related sedimentation; emplacement of ophiolites at oceanic spreading centers; regional thrust sheets; and metamorphic core complexes.

Ages of Pre-Mesozoic Orogenies in Northern Andes Ranges of Venezuela and Colombia *Philip O. Banks and Reginald Shagam* Case Western Reserve University, Cleveland, Ohio.
NSF Research Program: Geology
Grant No: EAR 78-23671

Case Western geologists are investigating patterns of mountain building and rock melting in the northern Andes Mountains within the Santander Massif (Colombia) and the Perija Ranges (Colombia and Venezuela). By field mapping and petrologic studies in the laboratory, their purpose is to understand the positions of the colliding plates in that region before the uplift of the Andes in Mesozoic time. They want further to decipher the origin and timing of plutonism (deep rock melting) and metamorphism (rock alteration by intense heat and pressure) in relation to plate movements in the region.

Questions of mineralization are not addressed directly, but the research is designed to unravel background problems in the tectonics, magmatism, and metamorphism of an Andean convergent plate boundary. These background problems inevitably hold clues to the accompanying metallogenic (ore forming) processes of the area.

Case Western geologists collect samples from a granite outcrop on the Rio Canagua in the central Venezuelan Andes. Lew Burkley (facing camera) did his PhD thesis on the geology in the region and now serves on the faculty of Radford College, Virginia. Pablo Kar, (seated) is a Venezuelan national who completed his thesis at Case Western on the geochronology of the area. Don Luis Molina (right) is a local guide who showed where the rocks are found.

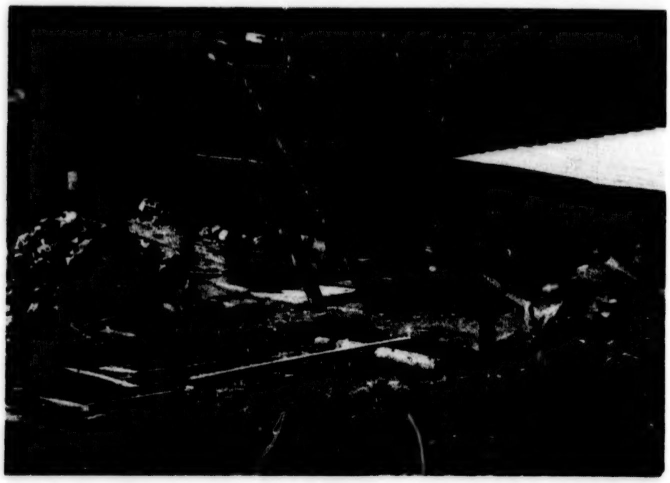
Knowledge of this region of the Andes bears on reconstruction of plate boundaries and the pre-Mesozoic history of western North America. Since many ore deposits form at convergent plate boundaries, this research potentially will advance our knowledge of deep mineralization in important metallogenic locales in the U.S.

Geologic Evolution of the Kings Mountain Belt, Southern Appalachian Mountains *J. Robert Butler*, University of North Carolina, Chapel Hill, North Carolina.
NSF Research Program: Geology
Grant No: EAR 78-26127

The Kings Mountain Belt, located in the Carolinas, is noted for lithium and tin mineralization. The main objective of the University of North Carolina study of these metamorphic and intensely folded rocks is to determine their role in the geologic evolution of the Southern Appalachians. Knowledge gained may be valuable to understanding the occurrence of ore deposits in this very large region.

Some geologists consider the Kings Mountain Belt to be a window showing the North American plate exposed between thrust sheets of the overriding African plate. This profound tectonic event occurred after at least one opening of the proto-Atlantic Ocean and was produced by Africa colliding with North America as the ocean closed. As the Atlantic reopened, the two continents separated with a huge slice of Africa resting atop the eastern margin of North America, referred to as the Appalachian orogen.

If this hypothesis is true, the Kings Mountain Belt may hold clues to the geology of Piedmont rocks beneath the vast African thrust sheet. Already, there is speculation and exploration for oil and gas accumulations in folded structures beneath the thrust sheet. Since tin and lithium ore are known in the Kings Mountain Belt, further knowledge of the ancient plate collision, overthrusting, and accompanying metallogenesis may very well shed light on deep mineral resources below the thrust sheet.



This is the Dixie-Carolina No. 2 Shaft on gold prospect active in the mid-1960's near Smyrna, South Carolina. Although it produced no gold, other mines nearby have, as well as barite, iron, kyanite, manganese, pyrite, lithium and tin. A research goal is to determine the nature and origin of the deposits.

Structural and Petrologic Evolution of the San Juan Islands, Washington, and Adjacent Related Areas *Darrel S. Cowan*, University of Washington, Seattle, Washington.
NSF Research Program: Geology
Grant No: EAR 79-10827

Investigation of deformed rocks in the San Juan Islands in Washington State may clarify the plate tectonic history of the Pacific Northwest and thus contribute to the exploration for mineral deposits.

This research is a field study in an area of complex and still unclear plate tectonic history. Mesozoic rocks of the San Juan Islands apparently originated outside of the region of Puget Sound. Where did these rocks come from? Were they once part of the Asian plate and then transported eastward to collide with North America? Or were they part of the North American plate to the south and transported northward by large-scale strike-slip faulting?

Massive sulfide ore bodies have been found on nearby Vancouver Island, and these deposits have been identified as volcanogenic-island arc type mineralization like those of the Kuroko District in Japan. Kuroko-type deposits are closely associated with subduction-zone plate margins.

If plate collision and subduction are found to be the controlling tectonic mechanisms in the Puget Sound region, this class of base metal deposits may be ubiquitous at depth in this complexly deformed geological environment. If transport from the south is the more likely explanation, the observed ore deposits may relate more to subduction as once occurred farther to the south in California. Either way, this research elaborates the tectonic framework of some observed mineralization, and it may afford a new basis for exploration of more extensive ore bodies.

Volcanism, Tectonism, and Ore Deposition in Fiji and Indonesia *James B. Gill,* University of California, Santa Cruz, California.
NSF Research Program: Geochemistry
Grant No: EAR 76-84065

James Gill and four graduate students of the University of California, Santa Cruz are doing field work in Fiji and Indonesia. This research concerns the tectonics and generation of magma at convergent plate boundaries as exemplified in Fiji and Indonesia. The relationships between island arc volcanism and porphyry copper mineralization will be studied as will the chemistry of active volcanoes bordering the Molucca Sea arc-arc collision zone.

Comparisons will also be made between basaltic lava rocks in this modern island arc region and Archaean greenstone belts found on the continents. This latter effort is designed to test the thesis that the ancient, highly metamorphosed greenstones are represented by their modern analogs in the volcanics of the research area.

The study of copper mineralization is directly applicable in exploration for deep ore deposits. Broadly speaking, the overall tectonic and volcanic activity of an island-arc plate boundary is an important ore deposition enviroment. Better understanding of regional metallogenesis in this geodynamic setting will enhance the search for blind ore deposits, not only at similar modern plate boundaries around the world, but also in their analogs throughout the geologic record.

Geological Evolution of the Molucca Sea Collision Zone: Structural Geology, Stratigraphy, and Petrology of the Talaud Islands *James W. Hawkins and Gregory F. Moore,* University of California, San Diego La Jolla, California.
NSF Research Program: Geology
Grant No: EAR 78-22750

Investigation of a rare type of oceanic plate margin takes geologists from UCSD's Scripps Institution of Oceanography to the Talaud Islands in Indonesia. The unusual geodynamic phenomenon under study is the collision of two arc-bounded plates. The Talaud Islands lie between two parallel and merging subduction zones which separate the converging plates. Research results will be important in developing a realistic model of deformation, and ophiolite emplacement (sheeted dikes of oceanic basalt) in similar settings inferred from the geology of older continental rocks.

Scripps geologists are examining the internal structure of the collision zone by making several geologic transects across the Islands. The project's petrographic, geochemical and paleontological studies link on-shore geology to geophysics in the adjacent sea.

This is a complex geological environment where two arc-bounded plates are converging. The research is useful background on the occurrence of ophiolite sequences in this tectonic setting since some ore deposits are found typically in ophiolite terrains. This project helps to understand such zones in complex folded mountain belts by close study of a young and currently active prototype in the Molucca Sea. With a sound scientific basis for deciphering the complex geology, the metallogenesis of such areas will be more readily discernible.

Greg Moore, Asst. Research Geologist, wades to an outcrop of pillow basalt on Karakelang Island, Indonesia, the largest of the Talaud Islands. This pillow basalt is a piece of oceanic crust that has been incorporated into the collision complex in the Molucca Sea.

Petrology of the Old Woman-Piute Range Plutonic Complex, Southeastern California *Calvin F. Miller,* Vanderbilt University, Nashville, Tennessee.
NSF Research Program: Geology
Grant No: EAR 78-23694

The Old Woman-Piute Range in California's Mojave Desert consists of granites (igneous intrusive rocks) and migmatites (high grade metamorphic rocks formed at extremely high temperature and pressure). The rocks of this mountain range not only formed deep in the crust and, therefore, may shed light on the geology of deep ore deposits in crystalline basement rocks elsewhere, but also the granites have a geochemical composition perhaps diagnostic of processes by which the North American continent grew on its Cordilleran or western margin.

The granites of the Old Woman-Piute Range are part of an inland belt of muscovite-bearing granites stretching from Sonora in Mexico to British Columbia. One of the micas, muscovite is a shiny, platy mineral which has abundant aluminum. Some geologists believe the aluminous muscovite granites are derived from melting of deeply buried sediments.

Since granites west of the belt are largely devoid of muscovite and since the belt roughly corresponds to the western limit of Pre-cambrian crystalline basement, the Vanderbilt project may unravel some of the processes of deep crustal

Vanderbilt undergraduate Joseph Gilbert and Principal Investigator Calvin Miller take rock samples at outcrop in the Piute Mountains, southern California.

Ann Katherine Sparks, Vanderbilt graduate student, studies rock samples from the Piute Mountains via a powerful microscope. Her reseach contributes to her masters thesis.

melting and extreme metamorphism and deformation that may have contributed to the accreting continent. Although not directly related to ore mineralization, the field mapping and laboratory analysis of this research addresses deep crustal processes that greatly influence the regional distribution of minerals.

Pre-Tertiary Tectonic Framework of the Central and Western Mojave Desert *Elizabeth L. Miller,* Stanford University, Stanford, California.
NSF Research Program: Geology
Grant No: EAR 78-22763

Historically, most of the Nation's non-ferous mineral wealth has come from the western U.S.—a vast region from the Rocky Mountains to the Pacific, which geologists call the Cordillera. Mineral resources greater than those already discovered will be found in deeper deposits if fundamental problems of Cordilleran geology can be solved.

Elizabeth Miller is studying one of these problems in the southern part of the U.S. Cordillera. Precambrian and Paleozoic (oldest and very old) rocks appear to have been truncated along their southern margin prior to the emergence of Mesozoic (moderately old) igneous rocks in the eastern Mojave Desert and Great Basin. However, the tectonic events (crustal movements by faulting, folding, etc.) that erased the record of these older rocks are not clearly understood. These tectonic events could have been responsible for and/or constrained the formation of ore deposits in the region.

Field mapping in the Western Mojave and radiometric age dating of rocks are conducted to clarify the tectonic and thermal events that produced the Mesozoic volcanic and plutonic (igneous rocks that did not vent at the surface) arc terranes. The Stanford geologists want to unravel the greater complexities of the western Mojave, caused by metamorphism and the juxtaposition of dissimilar rock types. Thus, they hope to understand in better detail how ancient plate movements profoundly changed the face of the Cordilleran margin of the continent and contributed to Mesozoic mineralization, which is widely distributed in copper and other deposits.

Tectonic Significance of Paleozoic Basement Terranes in the West-Central Sierra Nevada, California *Richard A. Schweickert,* Lamont-Doherty Geological Observatory, Columbia University, Palisades, New York.
NSF Research Program: Geology
Grant No: EAR 78-23567

Recent geological field research has revealed that a major mylonitic thrust zone of regional extent in northern California separates an upper plate consisting of the lower Paleozoic (older) Shoo Fly Complex from the upper Paleozoic (younger) Calaveras Complex in the lower plate. The age and tectonic significance of the thrust is being investigated by Columbia University geologists.

The project will provide an important link between studies of allochthonous (transported by the overthrust) lower

Paleozoic terranes in northern California and autochthonous (unmoved or in place) terranes in the eastern Sierra Nevada and White-Inyo Mountains. This is essential to correlating events and sequences across the Mesozoic Sierra Nevada batholith and, perhaps, with tectonic events in north-central Nevada.

This research contributes to reconstruction of the plate tectonic history of the North American Cordillera. This knowledge of fossil geodynamic events is essential to understand the metallogenesis of the western U.S. Improved understanding of the origins of metallogenic provinces in the context of the driving force of plate tectonics will eventually aid exploration strategies and technology.

Symposium and Field Conferences on the Caledonide Orogen *James W. Skehan*, Weston Observatory, Boston, College, Weston, Massachusetts.
NSF Research Program: Geology
Grant No: EAR 79-03008

In a spirit of international cooperation, over 300 geologists from 18 countries met last fall in Blacksburg, Virginia to exchange information on early Paleozoic orogeny (mountain building) in lands bordering the North Atlantic Ocean. A better understanding of the geodynamics of orogeny may enhance efforts to locate valuable ore deposits.

The conference was part of a ten year activity called the International Geological Correlation Program (IGCP) to promote coordinated analysis of the Caledonide Orogen, a mountain system which resulted from upheavals created by the opening and closing of the proto-Atlantic Ocean in late Precambrian and early Paleozoic time. A major objective of the IGCP project is to reconstruct the Paleozoic history of the Atlantic borders of North America, Europe and Africa.

In addition to the Blacksburg symposium, two field trips were made to the northern and central Appalachian Mountains. The conference gave American geologists the opportunity to present their findings on the Paleozoic geological history of eastern North America to an international audience and to hear critiques of their ideas. The scientists also met to compile geological and tectonic maps of the eastern and western margins of the orogen.

The Ruby Mountains—East Humboldt Range, Nevada: A Case Study of a Cordilleran Metamorphic Core Complex *Arthur W. Snoke*, University of South Carolina, Columbia, South Carolina.
NSF Research Program: Geology
Grant No: EAR 79-04204

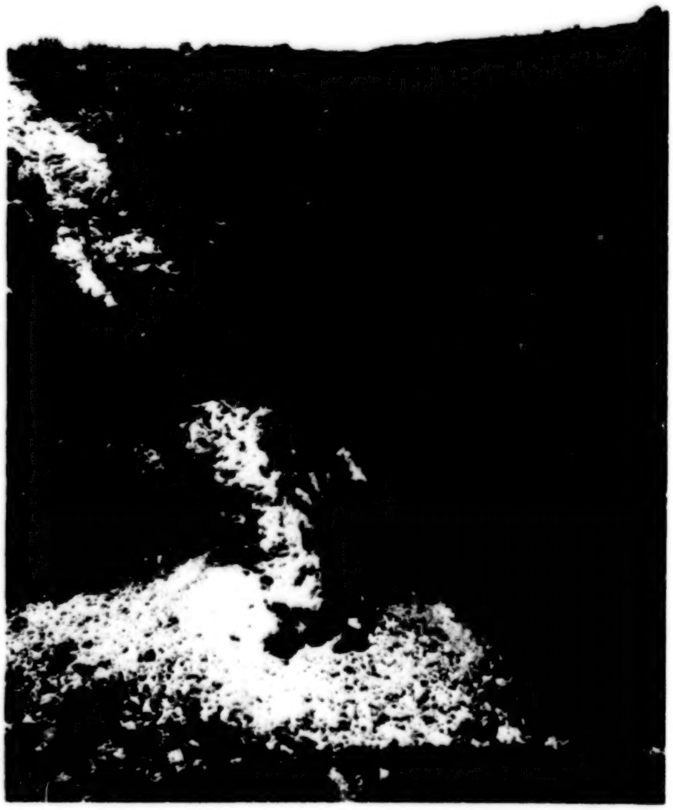
This research is a detailed study of an extensive metamorphic core complex in northeastern Nevada. Such a geologic feature has a broad core (10–100 miles wide) of metamorphic rocks overlain by a mantle of deformed but unmetamorphosed sedimentary rocks.

The rocks of the Ruby Mountains core complex, thought originally to have been Precambrian in age, have in more recent years been regarded by some geologists as metamorphic rocks of Paleozoic to Early Mesozoic age. Arthur Snoke and his colleagues are working on a consistent chronology of igneous/metamorphic and tectonic events producing the complex geology of the area.

The research will provide new understanding of the orogenic mechanisms responsible for core complexes found in a broad zone from Alaska to Sonora. Thus, this research is expected to advance the theoretical integration of core complexes, which are such an evident part of the North American Cordillera, into a reconstruction of the plate tectonic history of the western U.S.

In this broader objective this research contributes to basic knowledge of deep mineral resources. For it is in understanding how thermal and tectonic processes have actually worked and how their effects in the rocks are distributed in geologic time and space that metallogenic processes in the Cordillera make new sense. With a more fundamental grasp of the wider geologic framework in which ore deposits occur, their discovery can be effected with greater confidence and efficiency.

Tectonic Evolution of the Havallah Sequence, Deposits of a Late Paleozoic Marginal Sea, Northern Nevada *Walter S. Snyder, Hannes K. Brueckner and Richard A. Schweickert*, Lamont-Doherty Geological Observatory, Columbia University, Palisades, New York.
NSF Research Program: Geology
Grant No: EAR 79-05722



Walter Snyder, Research Associate at Columbia's Lamont-Doherty Geological Observatory, locates an outcrop in Nevada important to the study of the Havallah sequence. A sharply dipping, highly weathered (oxidized) metalliferous sediment lies on top of a horizon of copper rich greenstone (altered volcanic sea floor).

Objectives of this research at Columbia are the metallogeny, structure, sedimentology, petrology and geochemistry of the Havallah sequence, presumably a late Paleozoic marginal basin complex in northern Nevada. These rocks are thought to be allochthonous, that is, they formed somewhere to the west, on the margin of the North American continent, and were subsequently thrust to the east overriding the continent. This study is a detailed attempt to understand the critical role of the Havallah sequence in the plate tectonic reconstruction of the U.S. Cordillera.

Mapping of anomalous mineralization in the Havallah sequence is a feature of this research, and this will contribute to understanding the metallogenesis of stratabound (conformable to the bedding of sediments) deposits in these rocks. However, more important to the topic of Deep Mineral Resources, the new knowledge concerning Cordilleran (western North America) plate tectonic history is the basic background or geological framework necessary to understand the metallogenesis of this vast region.

The Columbia geologists are employing new techniques, not employed in earlier studies of the Havallah sequence, e.g., mapping lithotectonic units, analyzing the structures of minor folds, and extracting microfossils from chert, a compact rock consisting of microcrystalline quartz. The general results of this study will be applicable to similar terrains (both older and younger), especially in the western U.S., Alaska, and the Appalachian folded belt.

Support of the U.S. Geodynamics Committee *Pembroke J. Hart,* National Academy of Sciences, Washington, D.C.
NSF Research Program: Geophysics
Grant No: EAR 79-01089

The U.S. Geodynamics Committee (USGC) is a unit of the National Academy of Sciences. The USGC was established in 1969 to develop long-range plans for solid-earth studies in the United States, especially taking account of the new developments in plate tectonics. In 1970, the USGC was asked to serve as the U.S. committee for the International Geodynamics Project. The USGC has carried out its work largely through the recommendations developed by its sixteen reporters and their associated working groups.

The USGC provides advice and guidance for U.S. research activities related to plate tectonics and its implications for a wide range of earth science topics. It has given increased attention to resource applications of geodynamics as indicated by its 1978 document entitled "Crustal Dynamics: A Framework for Resource Systems." As this emphasis continues, more helpful guidance for research related to Deep Mineral Resources will be available to U.S. earth scientists.

B. Metallogenesis

Metallogenesis is that branch of economic geology concerned with the origins of ore deposits. As mining geologists understand more thoroughly how Nature has concentrated economic materials, which are quite scarce in most rocks, the exploration for new mineral resources becomes more effective through full, accurate use of new geologic clues. NSF research in metallogenesis focuses on various classes of deposits, i.e., oceanic hydrothermal manganese and other base metal sulfides; volatile and refractory base metals related to continental volcanism; syngenetic (or sedimentary) and/or stratiform deposits (post-sedimentary but conformal to bedding); and porphyry copper deposits. The following eleven research projects received IBR support in 1979.

Manganese Deposits of the Franciscan Assemblage: Tests for a Hydrothermal Sea Floor Origin *David A. Crerar,* Princeton University, Princeton, New Jersey.
NSF Research Program: Geochemistry
Grant No: EAR 79-04884

David Crerar operates gas chromatograph at Princeton University.

Graduate student Jay Namson is examining manganese ore with a hand lens at the South Thomas mine in Mendocino County, California.

This rock was retrieved by the ALVIN at the 21°N site on the East Pacific Spreading Ridge. It is rich in sulfide minerals of zinc, copper and iron.

David Crerar and his research team are engaged in detailed field and laboratory studies of manganese deposits in the northern California Coast Ranges. The objective of the project is to distinguish between a sedimentary and a hydrothermal origin for the manganiferous cherts, which are compact rocks composed primarily of microcrystalline quartz.

The investigators are exploring the relationships between manganese ore, cherts, and underlying basalts. If the ores prove to be hydrothermal in origin, the study would make important contributions to our understanding of metallogenesis involving hydrothermal seawater-basalt reactions in the vicinity of mid-ocean ridges. Tests will be made for halos of metal depletion or enrichment in the vicinity of ores.

High Temperature Water Sampling and Instrumentation *John M. Edmond,* Massachusetts Institute of Technology, Cambridge, Massachusetts.
NSF Research Program: Seabed Assessment
Grant No: OCE 77-23471

During the last three years John Edmond has sampled and chemically analyzed hydrothermal water which has circulated through the oceanic crust and is discharged back into the sea water. Study of these fluids is important in understanding the processes which alter the oceanic crust, form mineral deposits, and control the long-term chemical composition of sea water.

While exploring the mouth of the Gulf of California in the submersible research vessel ALVIN in September 1979, oceanographers made an exciting discovery which may make available an entirely new mineral source. At 21°N latitude, the explorers identified "chimneys" out of which poured very hot fluids rich in zinc (Zn), copper (Cu), and iron (Fe).

The current two-part project is a sequel to that geological breakthrough. In the first phase, scientists are designing and constructing temperature sensing and water sampling systems capable of handling hydrothermal waters at temperatures above 350°C. The second half of the project is devoted to the building of an ALVIN hot water alarm system to ensure safe operation.

A companion project installed the equipment on ALVIN and sent a technical field team involving MIT, Scripps Institution of Oceanography, and Harvard University scientists back to the hydrothermal springs for actual measurements in November 1979.

Study of a Deep-Sea Hydrothermal Field at a Gulf of California Spreading Center *Peter F. Lonsdale and Victor D. Vacquier,* University of California, San Diego, La Jolla, California.
NSF Research Program: Submarine Geology and Geophysics
Grant No: OCE 79-08811

In July 1980, scientists from the Scripps Institution of Oceanography will take a 28-day exploration cruise into the Guaymas Basin of the Gulf of California. Knowledge gained from the project may improve our understanding of ore deposition at oceanic spreading ridges, shed light on the geochemical systems beneath the ridges, and facilitate mineral searches in the world's oceans.

The mission involves geophysical and geochemical studies of the hydrothermal system of the Guaymas Basin. The basin is ideal for study because its continental environment is similar to the spreading axis of the Red Sea, which is now a classic example of metalliferous sediments in active formation of rich ore deposits. The project will complement exploration efforts by the drill ship *Glomar Challenger* at the same hydrothermal field. Peter Lonsdale has also undertaken similar field programs at the Red Sea, East Pacific Rise, and the Galapagos Rift.

The research crew will employ deep tow sonars and cameras to develop geological maps of the submarine hydrothermal field, and the maps will be used to elucidate tectonic and heat flow patterns. In addition, the scientists will dredge and core the hydrothermal field's sedimentary cover to obtain samples for mineralogic and chemical analysis.

Geologic and Petrologic Studies in Southern Chile: Detailed Studies in Selected Areas of an Active Plate Margin *Ian W. Dalziel and W. Ian Ridley,* Lamont-Doherty Geological Observatory, Columbia University, Palisades, New York.
NSF Research Program: Geology
Grant No: EAR 79-06308

Mineral-laden hot water spews out of a natural "chimney" or fumarole formed by deposition of metalliferous mud at its lip. Subsequent measurements at the 21°N site with equipment obtained under the MIT grant (page 13) showed these hydrothermal fluids to be 350°C at several different vents.

Scientists aboard the exploration ship ALVIN made an exciting geological discovery near the Gulf of California in September 1979. At 21°N latitude, the explorers identified "chimneys" out of which poured thermal fluids rich in Zn, Cu and Fe.

To follow up on the ALVIN's discovery and better to understand metallogenesis on the sea floor, Columbia University geologists are currently involved in an investigation of an ophiolite complex in southern Chile. An ophiolite complex is a mass of rocks which formed from volcanic and hydrothermal processes occurring near mid-ocean spreading centers.

Since ophiolite complexes are associated with several classes of base metal ore deposits, the project may enhance mineral exploration efforts. Moreover, the research should help unravel the tectonic history of the region.

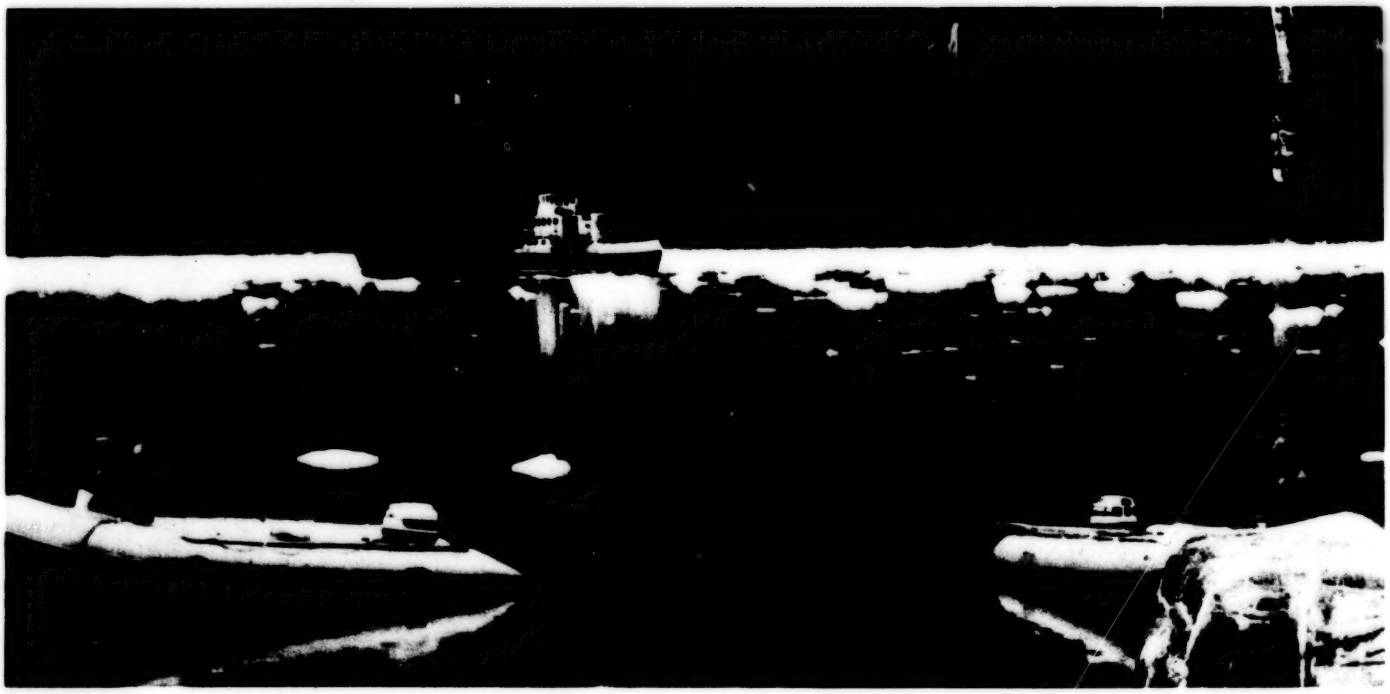
With cooperation from Chilean university and government geologists, American scientists are able to carry out significant geologic and petrologic studies. Data from the study will be of interest to understanding the development of oceanic crust and of metallogenic provinces.

Oceanic Serpentinites: Role of Seawater-Peridotite Interaction *William E. Seyfried Jr.*, University of Minnesota, Minneapolis, Minnesota.

NSF Research Program: Submarine Geology and Geophysics

Grant No: OCE 79-08569

The extensive occurrence of serpentinized peridotite within the oceanic crust is a challenging subject for geochemists. Peridotite is an igneous rock thought to be derived from the upper mantle. Its composition of silica (SiO_2) is one of the smallest known in the earth's crust among igneous rocks. Serpentinization is a little understood process



Two Columbia geologists on the shore of an ice-filled fiord in inflatable zodiacs. In the background is the research vessel HERO, which is owned by NSF and is the keystone of the research effort in southern Chile.

Ian Dalziel, Associate Professor of Geology, comes upon an interesting outcrop in southern Chile. It shows a sharp fold in the basement complex of Cordillera Darwin.

of hydrothermal alteration where water (H_2O) is chemically combined with the abundant ferromagnesian minerals of peridotite.

The research is experimental geochemistry of seawater peridotite reactions. It examines serpentinization within the oceanic crust, particularly along transverse fault zones of the Atlantic Ocean, e.g., Romanche, Vema, and Kane fracture zones. The serpentinization reactions are very possibly responsible for formation of metalliferous deposits in these zones, both on the sea floor and in the volume of hydrothermal circulation below. For this reason the research is expected to contribute new basic knowledge on the metallogenesis of some deep ore deposits.

The objective of the project is to characterize the chemical, mineralogic, and isotopic changes caused by the serpentization of oceanic peridotites. The investigators are examining reaction mechanisms, rates of alteration of igneous minerals, and direction and magnitude of chemical exchange in the course of this geochemically important process.

Geochemistry and Geochronology of W-Sn-Sb-Hg-F Mineralization in Northern Mexico

Stephen E. Kesler, University of Michigan, Ann Arbor, Michigan.

NSF Research Program: Geochemistry

Grant No: EAR 79-04894

The elements tungsten (W), tin (Sn), antimony (Sb), mercury (Hg), and fluorine (F) are thought to be the key

William Seyfried starts to remove a crushed rock sample from his Dickson-type rocking "bomb" apparatus. The "bomb" is a high temperature-pressure vessel for simulating geochemical reactions deep in the earth.

Martin Menzies, a post doctoral fellow in Minnesota's Department of Geology, uses a mass spectrometer to analyze reaction products from the rocking "bomb" experiments.

to understanding Cenozoic metallogenesis in northern Mexico, as well as evolution of Cenozoic mineral provinces elsewhere in the world. Ores of each element occupy well-defined belts in northern Mexico, and these belts overlap wide zones of copper-zinc-lead-minor silver (Cu-Zn-Pb-(Ag)) mineralization and gold-silver (Au-Ag) mineralization. It is fortuitous that these types of deposits are abundant and commercially developed in northern Mexico. New insight on the origins of these deposits will be applicable to similar deposits around the world, including blind ore deposits of these types in the U.S.

Building on past research in the region, Stephen Kesler and his colleagues are pursuing answers to these questions: 1) What is the age relation between W-Sn-Sb-Hg-F mineralization and the Cu-Zn-Pb-(Ag) and Au-Ag mineralization? 2) Is the W-Sn-Sb-Hg-F mineralization related to any particular igneous or tectonic feature of Cenozoic evolution? and 3) Does the source of metals in W-Sn-Sb-Hg-F deposits differ from that in other deposits of northern Mexico?

The research involves collection of representative samples for K-Ar age dating of the ore deposit and host rocks, geochemical studies of related volcanic rocks, mineralogical and fluid inclusion studies of the ores, and lead isotopic geochemistry of the ore deposits and related rocks. Cooperation with the field effort is provided by the Mexican Consejo de Recursos Minerales, and the laboratory work is carried out in cooperation with the University of Alberta and Ohio State University.

Stephen Kesler (left), Principal Investigator, stoops beneath the low roof of a Mexican mine noted for its celestite ore (strontium sulfate). It is in an area of important fluorite (calcium fluoride) deposits in the Sierra de Paila, Coahuila, Mexico.

Investigation of the Formation and Metallization of Ore-Bearing Breccia Pipes, Northern Sonora, Mexico

Frederick J. Sawkins, University of Minnesota, Minneapolis, Minnesota.
NSF Research Program: Geochemistry
Grant No: EAR 79-02958

University of Minnesota geologists are studying the metallization of ore-bearing breccia pipes in Northern Sonora, Mexico. Research results may provide valuable information concerning the location of blind ore deposits.

The volcanic arc and plutonic rocks of late Mesozoic age in northern Mexico contain a number of metallic ore deposits closely related to the intrusive magmatism. The metallogenesis is clearly associated with the subduction zone tectonics of an ancient plate boundary. Among the deposits are a series of copper (Cu), molybdenum (Mo), and tungsten (W) bearing breccia pipes in northern Sonora. A breccia pipe is a narrow body of rock that extends very deep and cuts across intervening rock formations. It consists of sharp, angular fragments immersed in a fine-grained matrix that is often mineralized with metallic ores.

This research examines the breccia pipes in their geologic and structural setting, breccia fragment size, shape and orientation, fluid inclusions (tiny bubbles captured in a crystallizing rock mineral), and alteration minerals. The purpose is to find the cause and mechanics of breccia pipe formation, especially collapse pipes, and the geochemistry of metallization and alteration events.

In particular, the project is concerned with the nature of the upper boundary of pipes and the causes of metal and alteration zoning to be found there. Since many mineralized pipes do not reach the modern erosion surface, this research will help in the search for blind ore deposits of this type.

Frederick Sawkins, Associate Professor of Geology inspects large slabbed samples of ore-bearing rock breccia from the Sonoran pipes. Fragment size, shape, and orientation offer clues on the origin of the base metal mineralization in the breccia pipe formations.

Origin of Oolitic Iron Deposits, Devonian and Cretaceous of North Africa and Israel

Franklyn B. Van Houten, Princeton University, Princeton, New Jersey.
NSF Research Program: Geology
Grant No: EAR 77-06007

Since 1977, Princeton has conducted a study of the late Cretaceous (about 100 million years) formation of oolitic iron ore (sediments containing rounded granules of iron oxides). Geology Professor Frank Van Houten has taken this study to the well-exposed oolitic iron formations of Egypt, Israel, and Libya. The Egyptian ores are late Cretaceous, while the Israeli formation is somewhat older (early Cretaceous). The Devonian ores in Libya are very much older (about 400 million years). Since the research is concerned with the metallogenesis of oolitic iron ores, it is potentially significant in understanding similar North American deposits such as the Clinton iron ore in Appalachia, and the Precambrian Skokoman ores in Labrador.

Currently, Van Houten is working with rock samples obtained during earlier field surveys. With his student assistants, he is examining the structural, textural, mineralogical and chemical characteristics of the oolitic layers and their enclosing deposits. More specifically, the researchers are trying to determine whether the ironstones formed as primary sedimentary deposits or in shallow seawater by diagenesis, i.e., post-sedimentation rock forming processes.

Paleomagnetism of Upper Paleozoic Sediments in the Appalachian Basin

Victor A. Schmidt, University of Pittsburgh, Pittsburgh, Pennsylvania.
NSF Research Program: Geophysics
Grant No: EAR 79-11094

The University of Pittsburgh is investigating the paleomagnetism of Carboniferous sedimentary rocks in the Appalachian Basin of Pennsylvania, Ohio, and West Virginia. (The Carboniferous includes the Pennsylvanian Period during which most of the world's coal was formed.) Concentrating on the abundant shales, siltstones and limestones in the basin, the project attempts to determine the polarity of the Earth's magnetic field at the time of deposition, as preserved in the remnant magnetism of the rocks.

So far, only reversed polarities have been found in Carboniferous sediments. The researchers expect to find genuine normal polarity and will then trace it laterally within the basin, hopefully setting up a framework for a comprehensive magnetostratigraphy for Carboniferous time.

This framework is potentially important to exploration for deeply buried ore deposits in the Carboniferous sections of the Illinois and Michigan Basins as well as the Appalachian (or Allegheny) Basin. There is possibly great mineral wealth in deep resources of the syngenetic (where ore formation is simultaneous with sedimentation) metalliferous black shales and replacement deposits of the Mississippi Valley lead-zinc type. Contributing to the future exploration of these deep basins, paleomagnetic methods are increasingly useful for stratigraphic correlations between wells and/or outcrops.

Investigations of the Porphyry Copper Metallogenic Province of the Southwestern United States *Leon T. Silver,* California Institute of Technology, Pasadena, California.
NSF Research Program: Geochemistry
Grant No: EAR 77-23507

The southwestern states are the leading copper producing region of the U.S. Their rich mineral endowment derives principally from igneous features which geologists call porphyry systems. The word porphyry refers to a siliceous crystalline rock (often quartz monzanite in composition) that in its molten state has penetrated shallow rocks from deep below. While still hot, the porphyry rock (or stock) forced groundwater in the vicinity to circulate in a hydrothermal convection cell. The movement of water tended to dissolve some ore minerals in a large volume of rock and to deposit them in valuable concentrations near the stock.

Cal Tech geologists are looking at the origins of this mineral wealth (and the rich deposits which await discovery at greater depth) and attempting to relate the metallogenesis to the plate tectonic history of the region. Through geochemical and petrological analyses, the investigators hope to: 1) establish a precise geochronology using unstable isotope analysis; 2) place porphyry copper deposits in the context of plate tectonic history of North America between 30 and 200 million years ago; 3) develop models for deep-seated source regions; 4) evaluate differentiation mechanisms which concentrate minerals in specific regions of deep igneous bodies; and 5) probe distinguishing geochemical characteristics of mineralized and barren porphyry systems.

This research will contribute new fundamental knowledge on the metallogenesis of ore deposits in a very large region of the U.S. The research looks at ore forming processes in magmatic source regions several miles deep as well as ore mineral distributions within plutons near the surface.

Furthermore, detailed understanding of these ore deposits within the plate tectonic setting of the region will enhance exploration efforts, not only in the U.S. Southwest, but also other regions typified by active or fossil converging plate boundaries. In particular, it is hoped that a sharper understanding of these processes will guide mineral exploration in discovery of deeper, more obscure mineral targets.

An Evaluation of the Nature and Evolution of Fracture Permeability During Pluton Cooling *Spencer R. Titley and Richard D. Beane,* University of Arizona, Tucson, Arizona.
NSF Research Program: Geology
Grant No: EAR 78-22897

At the Sierrita and Esperanza mining pits, located about 40 miles from Tucson, University of Arizona geologists are studying fractures in the ore bodies to determine permeability changes in porphyry copper systems. Their findings will add significantly to understanding of hydrothermal circulation near a cooling igneous rock.

As igneous rocks cool and crystallize near the earth's surface, hydrothermal convection is controlled by the permeability created by fracturing in surrounding rock. The rate of cooling changes when new fractures form or when old ones are filled by vein mineralization. Charting the fracture history of a porphyry system and study of the composition of veins and host rocks are steps toward understanding the emplacement of porphyry copper deposits.

The project is pertinent to mineral exploration because a knowledge of evolving fracture distributions adds the dimension of geologic time to current understanding of hydrothermal systems. A more thorough grasp of fracturing history is helpful in predicting the occurrence of copper by grade of ore, volumes of barren rock existing in a system, and the location of metal deposits in relation to fossil hydrothermal systems.

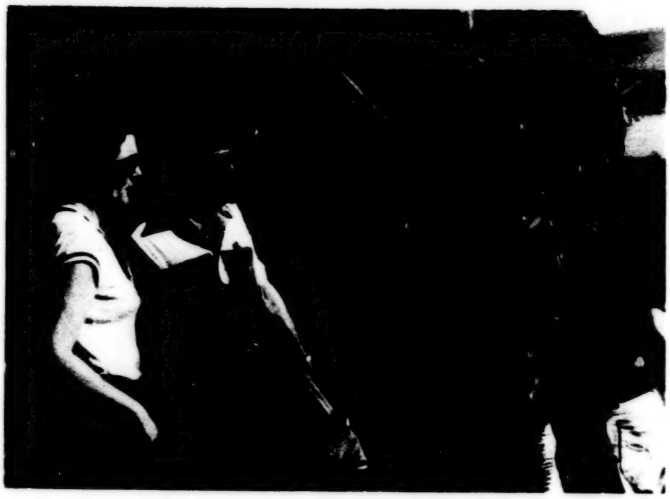
C. Deep Basement and Upper Mantle

The ultimate terrestrial origin of crustal rocks is the mantle. Processes that produce magma (molten rock) in the mantle, that emplace new material in the crust, and that alter pre-existing crustal material inevitably have profound effects on the distribution of ore minerals. Research under this subtopic contributes new knowledge on: 1) the geological origins of the Precambrian crystalline basement, which comprises the host rocks for much of the world's mineral wealth; 2) the structure and tectonics of the lower crust and upper mantle, which are source regions of deep mineral deposits; and 3) the geochemistry of deep igneous processes. The following ten research projects were supported by IBR in 1979.

Paleontology, Stratigraphy and Depositional Environments of Late Proterozoic Into Early Cambrian Rocks of the Tatonduk Area, Alaska *Carol W. Allison and Grant M. Young,* University of Alaska, Fairbanks, Alaska.
NSF Research Program: Geology
Grant No: EAR 79-03926

Information on the mineral composition and structure of rocks in eastern Alaska is scarce. If the region is left unexplored, the loss in terms of potential mineral resources may be substantial. As basic research in the geology of Alaska, this project may well contribute new knowledge: 1) on potentially mineralized placers and other stratabound deposits associated with very ancient glaciation and other sedimentary processes; and 2) on the very earliest plate tectonic history of the western margin of North America—a necessary framework for understanding Cordilleran metallogenesis.

The Precambrian sedimentary rocks of the Tatonduk Area in east-central Alaska, which may be the westernmost Precambrian of the North America craton, are overlain by a lower Cambrian (time of dramatic spread of life forms on earth) sedimentary sequence. Field work by a team of experts from the University of Alaska is under way to clarify



Carol Allison (left), Curator of the University of Alaska Museum, confers with her field team on the airstrip at Eagle, Alaska. Sandra White, graduate student, and Currie Palmer, Geology Professor (on right), both from the University of Western Ontario, described sampling sites for paleomagnetic studies for Dr. Allison and the team's pilot.

the stratigraphy, age, and paleontology of this critical section. Results are important in defining the base of the Cambrian system of North America and in understanding the major changes in plants and living creatures that occurred during this time.

Perhaps the most useful contribution to basic knowledge of mineral resources is the insight provided in the Tatonduk area on the latest times in the Precambrian era. Though deeply buried over much of the U.S., Precambrian rocks have untold potential for vast mineral wealth.

Archaean Clastic Sedimentation in the Pilbara Block of Western Australia and Related Crustal Evolutionary Implications *Kenneth A. Eriksson,* University of Texas at Dallas, Richardson, Texas.
NSF Research Program: Geology
Grant No: EAR 78-23407

Kenneth Eriksson of the University of Texas is studying well-exposed, sedimentary rocks in a region of Western Australia called the Pilbara Block. His objective is to identify rock types, sedimentary structures and stratigraphic sequences. Field and laboratory studies are aimed to interpret the composition and depositional environments of these ancient sediments in terms of relationships to land areas, continental rock-types, ancient seas, and former positions and movements of crustal plates.

Rocks of the Pilbara Block are of Archaean age, which is the oldest time division of the Precambrian era. This means these rocks are among the most ancient exposed on earth. Many valuable ore deposits are found in Archaean rocks in southern Africa and Canada. Eriksson is comparing his research data to studies of these African and Canadian rocks.

The basic knowledge to be obtained is useful background in understanding stratiform deposits that are known to occur in rocks of this age. New insight on paleoenvironments of Archean sediments are expected, and this may lead to new understanding of syngenetic ore deposition in that ancient geologic era. Although focusing on rocks in Australia, the research questions are pertinent to the oldest and often deepest continental rocks in North America.

Precambrian Geology and Geochronology of the Central and Northern Hualpai Mountains, Mojave County, Arizona *Howard L. Stensrud,* California State University, Chico, California.
NSF Research Program: Geology
Grant No: EAR 77-09040

Howard Stensrud, a geologist at California State University, is researching the Precambrian geology of metallic sulfide deposits located in the northern Hualpai Mountains of northwestern Arizona. Studying this region may improve mineral exploration efforts by clarifying the origin of massive sulfide ore deposits in Precambrian time.

The research examines two massive sulfide deposits which have been mined in the past. These ore deposits contain zinc and copper and minor amounts of lead. They are thought to be syngenetic, volcanogenic deposits, which means that they were formed nearly simultaneous with volcanic deposits of Precambrian age. A third deposit in the area has been mined for tungsten and has an unknown age and genetic relationship to a nearby granitic pluton.

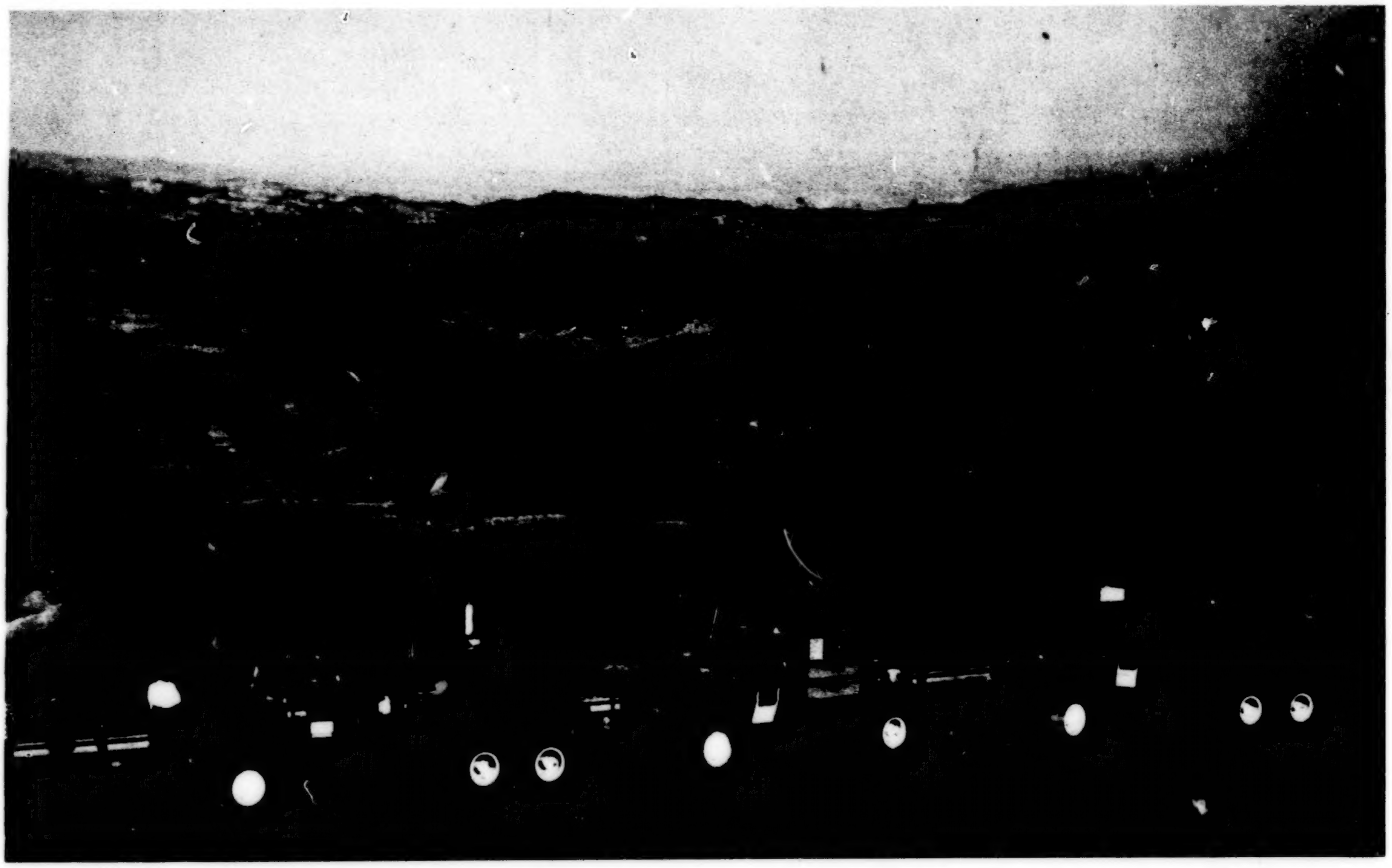
The work will advance our understanding of massive sulfide ore mineralization as it occurred in Precambrian time and has been modified by subsequent metamorphism and tectonic movements in the Earth's crust. A more thorough understanding of the ancient setting of these deposits will permit a more informed comparison with the growing body of knowledge on very much younger (and thus undeformed) deposits of island arc volcanic environments, e.g., Kuroko district of Japan. Since Precambrian rocks are typically very complex and buried deep beneath younger rocks, this research contributes to our grasp of the metallogenesis of deep mineral deposits.

Seismic Reflection Profiling of the Continental Basement *Jack E. Oliver, Sidney Kaufman and Larry D. Brown,* Cornell University, Ithaca, New York.
NSF Research Program: Geophysics
Grant No: EAR 78-23672

Earth scientists from five universities (Cornell, University of Wisconsin, University of Texas, University of Houston, and Princeton) have joined together in the Consortium for Continental Reflection Profiling (COCORP). COCORP was established to provide earth scientists with a mechanism for the application of modern high-resolution seismic profiling methods to studies of the continental crust and upper mantle to depths of 100 km. or more.

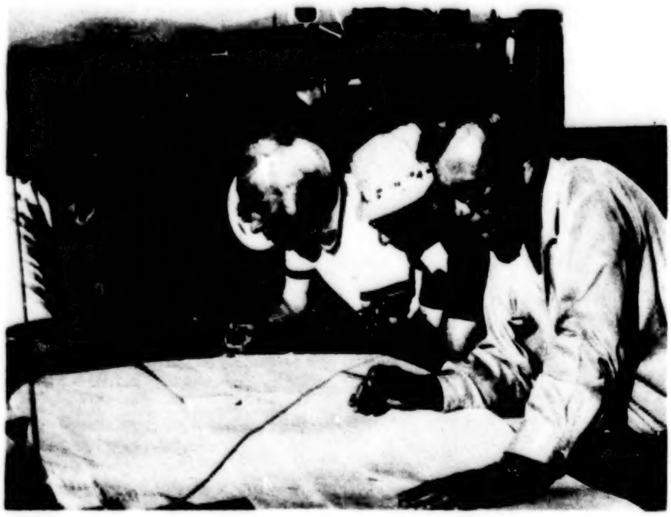
The continental basement almost certainly holds the key to some of the most fundamental questions of modern geology, particularly questions on the origin of the continents and their evolution. Scientifically, many illuminating surprises await us in details of this structure as deep sounding profiles are performed.

From the perspective of deep mineral resources, the geological knowledge obtained in this project provides the



COCORP vibrator trucks pause in Wyoming's Wind River Mountains between stations on a 100-mile seismic reflection traverse. The 15-ton trucks, mounted on jacks, vibrate up and down to generate a synchronous seismic wave in the ground that penetrates the base of the crust.

needful regional-scale data on rock environments beyond the reach of the commercial drill. In this technique geophysicists have a means to investigate the deep roots of mineral provinces and potential source regions in the upper mantle. Such exploration is prohibitively expensive by drilling.



COCORP scientists pore over seismograms in the field at Abo Pass, Texas, looking for reflections from deep within the crust. From left to right, they are: Fred Barr, Petty-Ray Corp.; Milton Dobrin, University of Houston geophysicist; Sidney Kaufman, Co-principal Investigator from Cornell University; and Harry Mayne, Petty-Ray Corp.

Geophysical Studies of the Wind River Mountains

Scott B. Smithson, University of Wyoming, Laramie, Wyoming.
NSF Research Program: Geophysics
Grant No: EAR 76-82878

Geologically, the Wind River Mountains of Wyoming are a large plunging anticline (a fold of stratified rocks) with considerable topographic and structural relief. Crystalline basement rocks form the core of the mountains along the axis of the fold. For this reason the area is a good place to investigate the deep Precambrian crust on the western edge of the North American craton (the crystalline core of the continent).

Evidently, these normally deep basement rocks have been elevated to the surface by the Wind River thrust fault, a tectonic feature recently discovered by deep seismic reflection data from the COCORP program. These data suggest the fault extends on a slant to the Moho, which is interpreted as the geophysical boundary between the crust and the mantle.

University of Wyoming geophysicists and geologists are studying the crystalline deep crust, both in outcrops in the Wind River Mountains and in analysis of COCORP reflection data. These studies lend themselves to basic understanding of the deep geological environments of possible ore deposits and/or source regions of ore forming materials. The area contains deposits of gold, iron, and molybdenum.

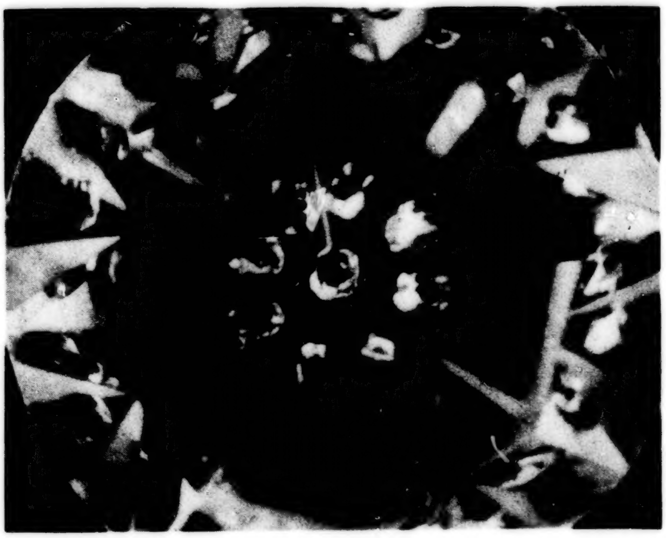
What do we do now? An early fall snow catches the seismic crew near South Pass in Wyoming's Wind River Range. Graduate student Bob Wyckoff (left) and Scott Smithson, Professor of Geology, take time to consider their next move for obtaining deep seismic structure in this old gold mining area.

Mineralogical and Geochemical Studies of Kimberlites, Xenoliths and Mineral Inclusions in Diamond *Henry O.A. Meyer,* Purdue University, West Lafayette, Indiana.
NSF Research Program: Geochemistry
Grant No: EAR 76-22698

Purdue scientists are investigating the geochemistry and mineralogy of rare rocks called kimberlites and samples of the mantle that are contained in them. Kimberlites are found in deep cylindrical rock masses, called pipes, that evidently are rooted in the lower part of the crust or upper mantle. These pipes contain xenoliths, which are fragments of country rock through which the molten kimberlite punched its way toward the earth's surface. Thus, the xenoliths of a kimberlite pipe are samples of a deep cross section of the crust and mantle source regions below it.

Kimberlite pipes also contain diamonds, whose origins in these unusual geological structures are not yet well understood. Beyond their importance as a commercial

Henry Meyer arranges for a new batch of inclusion-bearing diamonds to be delivered to his laboratory. These diamonds provide significant information regarding chemical processes in the upper mantle, where metalliferous crustal material is thought to originate.



This polished diamond contains a chromium-rich garnet inclusion. The multiple inclusion effect is due to the polishing. This type of garnet is rare in diamonds and is useful in determining physical and chemical conditions of diamond growth.

mineral, diamonds may have a fascinating story to tell through the tiny inclusions of other minerals inside them. Do the mineral inclusions show that diamonds form out of the kimberlite magma, or were they preformed at greater depth and carried up with the ascending pipe material?

Answers to these and other research questions will strengthen our yet dim knowledge of geochemical conditions in the mantle and how solid rock melts in some places to be transformed and emplaced in different mineral environments of the crust. Thus, earth scientists will understand better the ultimate mantle source regions of crustal mineralization and the igneous processes of their migration.

Ion Microprobe Study of Pre-Eruption Water Contents in Oceanic and Island Arc Volcanics *John R. Delaney*, University of Washington, Seattle, Washington.
NSF Research Program: Submarine · Geology and Geophysics
Grant No: OCE 79-09895

The research at the University of Washington utilizes the ion microprobe for *in situ* determination of small quantities of hydrogen (and thereby water) in sold materials on a scale of one micron. The technique is being refined and used to study the abundance, distribution, and mobility of water/hydrogen in pre-eruptive igneous rocks of oceanic and island arc volcanic systems.

Water in natural magmas has a strong effect on transport properties and phase equilibria in igneous systems and thus is a key parameter in models of volcanic eruption and concepts of magma genesis and mantle evolution. Water content and properties in silicate melts, as studied in this project, are also significant in the mechanisms of igneous intrusions that give rise to copper-molybdenum porphyry mineralization and of layered mafic intrusions associated with chromite and perhaps some nickel deposits.

John Delaney, Assistant Professor, is studying minute rock samples under a high-resolution polarizing photomicroscope.

Although this research is not examining rocks of direct mineral resource interest, many of the phenomena to be studied are generically the same, such as the diffusivity of water in a silicate melt and the flux of water across the boundary between a magma and the country rock. The ion microprobe method of investigation, as developed in this research, has a potential for future application in studies of igneous activity in the deep crust and upper mantle and the metallogenic processes that result from it.

Trace Element Distribution in Igneous Geologic Systems *Frederick A. Frey*, Massachusetts Institute of Technology, Cambridge, Massachusetts.
NSF Research Program: Geochemistry
Grant No: EAR 78-23423

By studying trace element abundances in rock samples taken from locations across the world, geochemists from the Massachusetts Institute of Technology (MIT) gain insight on the distribution of elements in the earth's mantle. Their study may advance our understanding of metallogenic provinces on a regional or global basis.

Most of the 92 elements in Nature occur in rocks in trace amounts (less than 1000 parts per million), and trace elements are often more sensitive indicators of many rock forming processes than the major elements of rocks. (Elements under study are: Rb, Sr, Ba, 1st transition series Sc to Ni, Y, Zr, Hf, Ta, rare earths, Th, and U.)

This research is very fundamental igneous petrology, but it is pertinent to metallogenesis in its focus on trace elements. Some of these elements constitute important ore bodies when found in high concentrations. More important, because trace element abundances are often more sensitive indicators than major element compositions, the MIT research is expected to unveil new insights on distribution of rock types in the upper mantle where most magmas form and igneous processes begin. This knowledge is basic to understanding the global distribution of minerals and the occurrence of metallogenic provinces.

Studies of Trace Element Behavior During Crystallization of the Makaopuhi Lava Lake, Hawaii *Larry A. Haskin and Marilyn M. Lindstrom* Washington University, St. Louis, Missouri.
NSF Research Program: Geochemistry
Grant No: EAR 79-04888

The Makaopuhi Lava Lake on the Island of Hawaii is a convenient laboratory for studying trace-element behavior in a magma (molten rock). It is a pool of lava that formed in the 1964–65 eruptions of Kilauea Volcano and slowly froze from its top and bottom toward the center. Geochemists from Washington University are studying which trace elements are drawn into the surface crust of the lava lake as it freezes and which are left in the liquid residue.

Trace element abundances are promising indicators of the type and extent of magma forming and modifying processes, and of the composition of source regions in the upper mantle. Thus, this study is expected to help understand the history of magma differentiation from origin in the mantle to crystallization in the crust or to venting in volcanic erup-

Marilyn Lindstrom, Research Scientist, lifts the lead shield housing the germanium-lithium detector used in instrumental neutron activation analysis (INAA) of trace elements in lava samples.

tions. Although Makaopuhi is a scant 15 years old, trace element distributions observed in its lava lake will shed light on igneous events of quite ancient geological age.

Since many ore forming processes are intimately related to igneous activity, this project may provide vital background to the origins of some types of ore bodies. In this way the exploration for deep deposits may be made more effective.

High Pressure Phase Equilibrium Studies Bearing on Mantle Evolution and the Generation of Basaltic Magma *Dean C. Presnall*, University of Texas at Dallas, Richardson, Texas.
NSF Research Program: Geochemistry
Grant No: EAR 78-22766

What happens in the mantle of the earth as rocks melt to form molten basalts that penetrate through the crust to erupt on the surface, such as at Hawaii? What peculiarities in the mantle source rocks cause melting at some places and not at others? Geochemists at the University of Texas at Dallas are doing research on these questions.

At Dallas, experiments are being made with natural earth minerals, i.e., lime (CaO), magnesia (MgO), alumina (Al_2O_3), and silica (SiO_2), that are major components of basalts. These rock minerals are subjected to melting temperatures and pressures up to those obtained in the mantle

Dean Presnall, Professor, makes measurements of composition of rock with the aid of a sophisticated instrument called an electron microprobe.

Dan Schulze, graduate student, holds a spinel lherzolite nodule from Salt Lake Crater, Hawaii. This rock is a sample of the earth's mantle about 20 to 40 miles deep.

(40 kb). Observations of melting and crystallization reveal the complex processes by which igneous rocks in the crust, having a large diversity of mineral compositions, are derived from parent magmas.

Since magmatic processes, at and remote from active plate boundaries, comprise a common driving force behind ore deposit formation, it may be vital to understand the yet elusive origins of magmas. Although metallic elements found concentrated in ore deposits are minor constituents of molten magmas, their origins and fractionation paths are greatly influenced by the dominant geochemical processes affecting the major elements.

D. Exploration Methods

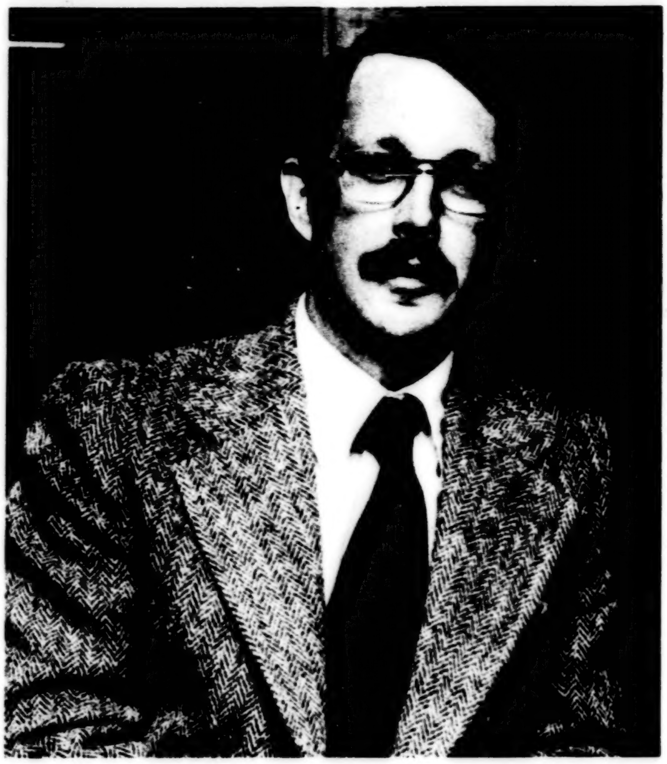
Instrumentation developments continue to benefit mining geophysics and commercial exploration programs, but dramatic new exploration methods will be needed in the future. These will come from advances in basic research. Presently, the most promising possibilities lie in the potential of the computer to handle large, complex data bases and to interpret them in geologic terms that relate to ore deposits. Five projects supported by IBR in FY 1979 include research in: knowledge-based expert systems; modeling of transient electromagnetic methods; computer induction and plausible inference; and computer vision and pattern recognition.

Knowledge-Based Consultation Systems *Bruce G. Buchanan*, Stanford University, Stanford, California.
NSF Research Program: Intelligent Systems
Grant No: MCS 79-03753

Bruce Buchanan deals with intelligent systems, in other words, the use of computers to assist in the analysis and solution of extremely complex technical problems often requiring immediate operational decisions. The type of intelligent systems under study in this project embody a large knowledge base in some technical subject and attempt to apply and interpret that knowledge in the analysis of a problem.

Up to now, the Stanford's research has centered on domain-specific (or subject-specific) rule-based systems, i.e., DENDRAL or MYCIN. The most useful features from these two systems are extracted to produce a generalized or domain-independent system called EMYCIN. EMYCIN will be capable of handling intricate reasoning tasks for which there are no algorithmic solutions. In essence, the system will be able to draw inferences and exercise symbolic reasoning skills, based in facts and associations supplied by experts.

The study emphasizes the use of large knowledge banks for computer-based reasoning, and the improvement of knowledge transfer from human experts to computer programs. The main objective is to encode and use human judgmental knowledge of many problem areas in a single framework. By facilitating both the encoding of expertise in a knowledge base and the use of task-specific information, this project could solve "real world" problems in contrast to artificial problems fabricated in simplified domains.



Bruce Buchanan, Adjunct Professor, believes that artificial intelligence, when performed by complex computer software, is potentially a powerful aid in solving scientific and complex technological problems.

There are several such problem applications to future needs in deep mineral resources. Progress has already been made at SRI International with the PROSPECTOR system, which is an expert consultation system for mineral exploration. Further applications in improved systems for deep mineral exploration are expected in this research as well as applications in complex technical problems in solution mining of deep ore deposits.

Transient Electromagnetic Modeling *Gerald W. Hohmann*, University of Utah, Salt Lake City, Utah.
NSF Research Program: Geophysics
Grant No: EAR 79-12447

In the search for mineral resources, the mining industry has exhausted most of the relatively shallow ore deposits. Mineral exploration efforts, therefore, increasingly focus on detection of deep ore deposits.

A leading geophysical technique for deep mineral exploration is the transient electromagnetic (EM) method whereby a strong current pulse is driven through a loop of wire, and the loop senses and records magnetic field decay characteristics of buried mineral deposits.

At the University of Utah, geophysicists are perfecting the EM system. They are striving to make a major advance in mineral exploration by: 1) developing numerical solutions for computer calculation of transient EM responses of conductive ore bodies; 2) testing computer algorithms by applying them to available exploration data; and

Mike Oristaglio, Research Associate, performs transient EM calculations with a portable computer terminal.

3) evaluating the effectiveness of frequency-domain and time-domain EM methods.

By successful solution of the problems addressed in this project, geophysical exploration will be more effective at the large depth expected for new deposits. The new more powerful methods of interpreting transient EM data will permit a greater success rate in geophysical prospecting.

Studies in Computer Induction and Plausible Inference *Ryszard S. Michalski*, University of Illinois, Urbana, Illinois.
NSF Research Program: Intelligent Systems
Grant No: MCS 79-06614

Computer-aided generation of hypotheses is a relatively little explored area of computer science. Development of knowledge-based expert computer systems is presently done through a laborious encoding of experts' knowledge.

Ryszard Michalski, Associate Professor of Computer Science, is flanked by research assistants Bob Stepp (left) and Tom Dietterich. They are introducing revisions in their experimental computer program at a remote terminal.

Michalski and his colleagues attempt to formulate principles and methods of computer induction which could improve the process of inputing knowledge to computer systems. These methods have also a potential for application in the automated analysis of empirical scientific data for detecting logical, functional, and causal relationships.

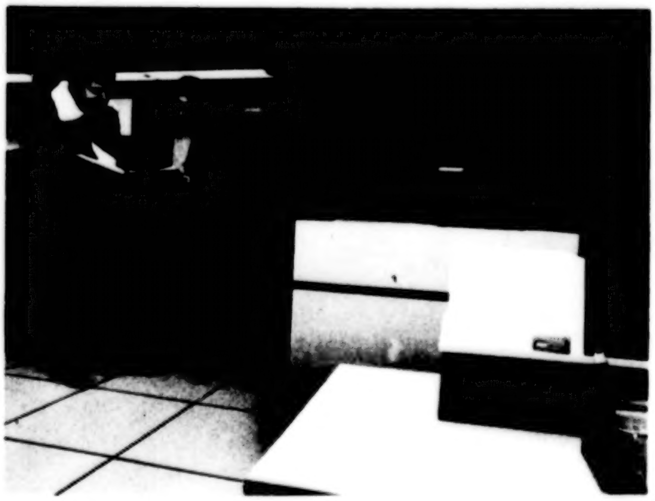
One of these, and the only one currently designed for minerals exploration, is the PROSPECTOR system at SRI International which was developed with USGS and NSF support. Therefore, improved computer science understanding of how efficiently to grasp large and complex data sets for use in rule-based expert systems will, among other applications, aid in future computerized expert consultants related to mining needs.

Certainly, applications in deep mineral exploration and in solution mining operations involve enormously complex input data sets of geological and engineering phenomena. The advanced capabilities in computer science can be employed in the difficult search for blind ore deposits and in the deep recovery of mineral values.

Parallel Algorithms and Computer Architectures for Image Processing and Pattern Recognition *Kai Hwang, Thomas S. Huang and King-Sun Fu*, Purdue University, Lafayette, Indiana.
NSF Research Program: Intelligent Systems
Grant No: EAR 78-18906

By tackling computer problems such as image processing and pattern recognition, computer engineers and scientists from Purdue University may develop a system capable of identifying deeply buried ore deposits.

At present, research on computerized image processing and pattern recognition is restricted by the excessively long running times required to test algorithms on general purpose computers. The major objective of the Purdue project is to derive general relationships between representative classes of algorithms and special purpose computer architectures in order to implement them efficiently.



Kai Hwang (right) and John R. Rice, Faculty Associate, examine experimental computer results at Purdue University.

The investigators are exploring two general types of algorithms: 1) real and generalized solutions of large linear systems; and 2) parsing algorithms for picture description languages. In addition, they are studying two general architectural concepts: 1) dynamically reconfigurable multiprocessor systems; and 2) associative processors and pipeline computers.

The research is relevant to Deep Mineral Resources by the potential applications in the remote sensing of deeply buried deposits. Recognition of deep structures in high altitude imagery may be enhanced greatly in the extraordinarily complex geological environments associated with most ore deposits. New techniques provided in this research may provide powerful new insight to understand the geological information in remote sensing imagery.

Computer System for Visual Interpretation of Natural Scenes *Edward M. Riseman* University of Massachusetts, Amherst, Massachusetts.
NSF Research Program: Intelligent Systems
Grant No: MCS 79-18209

In the near future, VISION, a computer system designed to perform visual interpretation of natural scenes, may be able to analyze unpolished sections of ore-related and other rocks. Such technological progress will have far-reaching benefits in specialized disciplines such as petrology, crystalography, and ore mineralogy, all of which are essential to the exploration of deep ore deposits.

Riseman's research project is to develop a computer system that analyzes color images of outdoor scenes, from segmentation of the raw two-dimensional sensory data to an output in terms of a linguistic (symbolic) representation of the three-dimensional world in view. A wide range of modular processes are being implemented to perform distinct functions associated with visual perception, such as analysis of shape, perspective, color and texture of objects, size of objects, etc. Some of the computer techniques correspond to human processes of drawing inferences based on prior knowledge and experience.

The research approach involves segmentation and analysis of 2-dimensional scene segments, which are processes potentially applicable in more specialized imagery, e.g., in petrography and SEM (scanning electron microscopy) studies. One can foresee analysis of large batches of unpolished thin sections of ore-related and other rocks by a system that received SEM and/or optical microscope images and automatically analyzes them by computer vision techniques investigated in this project.

Edward Riseman (left) looks at the digitized image of the front view of a house in the course of studies in computerized scene analysis. Allen Hanson, Associate Professor, moves the cursor on the screen with joystick control.

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